Journal of Computer and Knowledge Engineering, Vol. 9, No. 1, 2026. (59-72)

Ferdowsi University of Mashhad

Journal of Computer and Knowledge Engineering

https://cke.um.ac.ir

Information and Communication Technology Association of Iran

Exploring Metaverse Integration in Architectural Education for Immersive Learning and Creativity*

Research Article

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10.22067/cke.2025.92845.1155

Abstract *In response to the evolving demands of architectural education in the digital age, this study explores the transformative potential of the metaverse as a pedagogical platform. Grounded in a systematic review of interdisciplinary literature, the paper examines how the metaverse, with its immersive, interactive 3D virtual environments, can effectively address the limitations of traditional e-learning. Particularly, it can overcome the challenges related to spatial understanding, collaboration, and creativity that have long plagued design-based learning. While traditional e-learning modalities have supported architectural instruction to varying degrees, they often fall short in replicating the experiential richness of physical design studios. The metaverse, through its integration of virtual reality (VR), augmented reality (AR), and mixed reality (MR), offers a more dynamic and embodied learning experience. This paper evaluates the limitations of two-dimensional online learning environments and advocates for a shift toward metaverse-based education, where students can engage with architectural spaces, peers, and instructors in real time. By identifying key barriers—including technical, pedagogical, and ethical concerns—the study proposes a roadmap for effective integration of metaverse technologies in architectural curricula. It concludes by positioning the metaverse not as a replacement but as an evolution of studio-based education, capable of cultivating future architects equipped for a rapidly digitalizing built environment.*

Key Words Metaverse, Virtual Reality, Electronic Learning, Architectural Education, Immersive Learning

1. Introduction

Architectural evolution is intrinsically linked to socio-economic, political, and technological shifts. Consequently, technology and architecture maintain a symbiotic relationship, influencing both building production and architectural education [1]. Architectural education aims to cultivate creative and proficient architects capable of designing functional and aesthetically pleasing spaces. Architects require both specialized knowledge and creative vision, enabling them to conceive environments holistically [2]. Creativity, central to architectural innovation, is fostered through experiential learning [3]. University education plays a crucial role in developing this creativity, exposing students to diverse subjects including history, theory, technology, and social sciences. The dynamic interaction between professors and students within the classroom remains fundamental to architectural education [4].

In today's competitive global economy, educational quality is paramount, with universities playing a vital role [5]. Architectural education heavily relies on university studios, traditionally face-to-face, to foster both practical and theoretical knowledge, particularly creative thinking. Design studios, as spaces for design discourse, are central to this learning [6]. Recognizing the reciprocal relationship between environment and behavior, the design of responsive learning spaces significantly impacts educational outcomes. Research across sociology, environmental physiology, architecture, and education demonstrates that spatial variables influence attitudes, emotions, and behaviors. This understanding is crucial for art educators, as it directly shapes work habits and teacher-student interactions [7].

Reflecting centuries of influence from social, economic, and technological changes, architectural education requires a paradigm shift to meet 21st-century demands. This shift involves a move from traditional, face-to-face studio-based learning to more immersive, interactive learning environments. While traditionally emphasizing

* Manuscript received April 01, 2025, Revised October 10, 2025, accepted October 25, 2025.

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problem-solving, critical and creative thinking, interpersonal and intrapersonal skills, and technological and global awareness [8], future educational methods are expected to build upon these foundations. The shift towards the metaverse is a significant part of this paradigm shift, offering a more dynamic and embodied learning experience.

Since the 1970s, computer-based learning has been a key source of educational innovation. The rise of the World Wide Web and related technologies has transformed traditional education from a supportive tool to a fundamental shift [9]. E-learning, focusing on technology-driven education, particularly communication applications, offers advantages like cost-effectiveness, flexibility, and personalization compared to traditional methods [10]. By removing time and space constraints through asynchronous learning networks, e-learning facilitates flexible learner-instructor interactions. Online learning, virtual learning, distributed learning, network-based learning, and web-based learning are common modalities within this framework [11].

Studies indicate that while architecture professors recognize the value of e-learning, it often fails to meet the specific requirements of design education [12]. Leading institutions like the University of Sydney, Cornell University, ETH, MIT, the National University of Singapore, and the University of British Columbia have implemented virtual 2D design studios for global collaboration [13]. These studios facilitate design project collaboration, problem discussion, and solution testing, enhancing creative thinking through diverse peer and instructor interactions. However, 2D platforms suffer from several limitations, including restricted user perception, the perception of web conferencing as mere video calls, and inherent immobility that hinders interaction. Weak emotional expression also reduces the effectiveness of learning stimuli. For instance, the inability to fully perceive the depth and scale of a design in a 2D platform can hinder spatial understanding, a crucial aspect of architectural education (Ibid).

Advances in 3D modeling and internet technology have transformed educational perspectives, offering new avenues for enhancing higher education productivity and quality [14]. Addressing the limitations of 2D environments, a shift towards immersive 3D learning is crucial [13]. 3D environments, by increasing intrinsic motivation and engagement, serve as effective platforms for e-learning and distance education. They facilitate knowledge and skill transfer through realistic scenarios and richer collaborative experiences compared to 2D education [15].

The metaverse, a term coined by Neal Stephenson in his 1992 science fiction novel 'Snow Crash', is a collective virtual shared space, created by the convergence of virtually enhanced physical reality and physically persistent virtual reality. It is a digital realm that allows users to experience parallel lives virtually, blurring the lines between physical and virtual realities [16]. In education, the metaverse offers immersive, interactive learning environments with access to multimedia resources and facilitates global collaboration between students and instructors, transcending physical limitations [17].

In architecture, the metaverse offers revolutionary potential by providing immersive virtual environments for design exploration and visualization. Architects can create and modify 3D models, fostering intuitive spatial understanding and enhancing collaborative decision-making. This study explores the metaverse's capacity to improve architectural education, aiming to assess its impact on creativity, collaboration, and spatial understanding while identifying adoption barriers. Through a review of recent literature on metaverse integration in architectural education, focusing on immersive environments, technological advancements, and case studies, this study synthesizes theoretical frameworks to propose innovative approaches for interactive, collaborative learning, paving the way for future empirical research.

2. Literature Review

This multifaceted topic necessitates a systematic approach that integrates educational methodologies, technological innovations, and metaverse-like virtual environments. To manage the extensive research, the literature is structured into three key areas: technological advancements in e-learning, the unique challenges of architectural education, and the benefits of VR/AR integration. This framework provides a solid foundation for examining the metaverse's transformative potential in architectural education.

Scholars have extensively debated traditional education versus technological advancements. Educational reformers like John Dewey and Ivan Illich emphasized the importance of social interaction, often lacking in conventional classrooms, and advocated for fundamental shifts in teaching methods [18]. Nagy critiques teacher-centered classrooms as outdated and ineffective, leading to disengagement [19]. Conversely, Al-Tammemi highlights how educational technology advancements are reshaping learning, improving academic performance and outcomes [20].

The literature extensively discusses the benefits of distance education and technology's impact on traditional methods. Gunawardena and McIsaac assert that distance education is now globally recognized for delivering cost-effective, personalized, and interactive learning through multimedia and technological innovations [21]. Post-pandemic research [22] emphasizes that mobile devices offer more effective, accessible, and flexible learning opportunities than traditional methods. Guohong defines internet-based distance education as incorporating multimedia instruction, interactive displays, remote monitoring, classroom management, and online assessments, highlighting its resource richness, enhanced sharing, interactivity, and collaborative nature compared to traditional classrooms [23].

E-learning has become a central topic in modern education. The Canadian Council on Learning defines it as knowledge and skill development through ICT, facilitating interactions with content and peers. Tirziu and Vrabi highlights Oxford's definition of online learning via electronic media as comprehensive [24]. Aparicio view

technology in e-learning as an extension of traditional tools [25]. Ibrahim emphasizes e-learning's ability to overcome time, location, and access constraints but notes communication gaps between students and professors [26]. Mystakidis discusses limitations like inefficiency, fatigue, and mental health concerns, contributing to higher dropout rates [13]. Mystakidis suggests fostering engagement through tailored learning styles and aligning goals with evolving educational and socio-economic demands [27]. Monahan highlights that 3D environments, using games and animations, enhance student interaction and practical understanding [28].

Architectural education, distinct from engineering, is widely acknowledged for its comprehensive nature. Guney argues that it demands a multidisciplinary approach, extending beyond technical focus. He defines architecture as an art form requiring a broad understanding of engineering, mathematics, technology, economics, law, sociology, psychology, and aesthetics. Guney argues that this holistic perspective is crucial for developing aesthetic sensibilities in architectural practice. Network systems, exploration, and adaptable structures enhance efficiency and learning, reinforcing the art-engineering link with the design studio at its core [29]. Saleh emphasizes these components' role in maintaining the design studio as the convergence point for engineering and art [30]. Michael and Phocas similarly highlight the importance of integrating environmental education into architectural curricula for developing design within a multidisciplinary context [31].

Integrating virtual and physical environments is crucial in architectural education, where VR significantly enhances learning through advanced visualization and immersive experiences. Schumacher emphasizes the equal importance of virtual environments alongside physical ones, advocating for their simultaneous design [32]. Sirror highlights VR's rapid adoption in architectural education for improving program quality: since the early 2000s, VR and AR have provided advanced perceptual and visual capabilities, allowing architectural students to engage with diverse spatial experiences via 3D models, surpassing traditional design methods [33].

The metaverse, integrating VR and AR, enriches education through multifaceted interactions, immersion, and social communication. Aljanabi and Mohammed highlight its ability to seamlessly blend digital simulations with the physical world for real-time interaction, enhancing learning [34]. Kye describes the metaverse as an innovative educational platform fostering new social communication, creative freedom, and immersive experiences [35]. Frydenberg and Ohri note that while many institutions explore virtual immersive environments, few have launched metaverse-based courses. In their view, this platform enhances student engagement and satisfaction through immersive, hands-on VR activities, enabling experiences unattainable in the physical world [36]. Frydenberg further demonstrates that VR-based hands-on activities provide a more interactive and immersive learning environment, making abstract concepts tangible and increasing student satisfaction [37].

Recent studies highlight the metaverse's potential to revolutionize architectural education. For instance, Onecha focused on AR applications for construction and rehabilitation education [38], while Cininta proposed VR to reduce stress in online learning [39]. Tsiliakos investigated gamified spatial design within a metaverse framework [40]. Sopher & Lescop explored the Immersive Atelier Model (IAM) and Multi-user Virtual Environments (MUVEs) in remote studios, emphasizing how student-shaped MUVEs support learning and conceptualization [41].

Building upon the growing body of research on immersive learning environments, this study advances the discussion by positioning the metaverse as a comprehensive, practice-oriented framework for architectural education. Whereas prior studies have examined isolated dimensions—such as augmented reality for construction training, virtual reality for stress reduction and resilience, or gamified spatial design and immersive ateliers—this paper proposes an integrative synthesis that unites these strands into a coherent pedagogical and technological model. Specifically, it explores how the metaverse enhances spatial understanding, creativity, and collaboration in practice-based learning contexts such as architectural design studios. The originality of the present research lies not in producing new empirical data but in developing a conceptual and analytical framework that systematically connects insights from architecture, computer science, and educational theory. Through tools such as comparative 2D–3D learning matrices, SWOT analyses, and implementation roadmaps, the study articulates how metaverse environments can bridge the gap between theoretical instruction and experiential, studio-based practice. By framing the metaverse as an evolutionary extension of the design studio, rather than a substitute for it, this work contributes a unified perspective that clarifies its transformative potential, addresses technical and accessibility challenges, and establishes a structured foundation for subsequent empirical validation in architectural pedagogy.

3. METHODS

This study employs a conceptual and analytical methodology to investigate the integration of metaverse technologies in architectural education. Given the emerging nature of the metaverse in pedagogy, the research prioritizes theoretical synthesis and framework development over empirical data collection. A systematic literature review (SLR) was conducted to identify and analyze relevant scholarly works on immersive and virtual learning environments in architecture.

3.1. Systematic Literature Search

The search procedure was designed in alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol to ensure transparency and replicability. The process involved three sequential stages: identification, screening, and inclusion.

Databases and scope
The primary databases consulted were Scopus, IEEE Xplore, ScienceDirect (Elsevier), and SpringerLink, selected for their high-quality, peer-reviewed content in relevant fields. Google Scholar was also used to ensure comprehensive coverage of emerging studies and grey literature. The search covered publications from 2013 to 2025, spanning over a decade of developments in virtual and metaverse-based pedagogical strategies.

Search string
A comprehensive search query was developed and adapted for the syntax of each database. The final string used was: (“metaverse” OR “virtual reality” OR “augmented reality” OR “mixed reality” OR “extended reality” OR “XR” OR “immersive environment” OR “digital twin” OR “virtual campus” OR “virtual world”) AND (“architectural education” OR “architecture pedagogy” OR “design studio” OR “digital design” OR “architectural learning” OR “architecture teaching” OR “spatial learning” OR “collaborative design” OR “architecture curriculum” OR “remote learning” OR “e-learning”).
This query was used to retrieve studies related to the integration of immersive technologies and metaverse environments in architectural education and design pedagogy.

3.2. Inclusion and Exclusion Criteria
Studies were included based on the following criteria:
- Peer-reviewed journal articles, conference proceedings, or book chapters published in English.
- Explicit focus on virtual, augmented, or mixed reality applications within architectural or design education.
- Publication date between 2013 and 2025, reporting conceptual, methodological, or applied insights.

Exclusion criteria were:
- Non-academic, promotional, or non-peer-reviewed sources.
- Studies not directly related to the architectural or design education domain.
- Duplicate publications.

Note: While the systematic search was bounded by the 2013-2025 period to capture the modern technological landscape, a limited number of seminal works published prior to 2013 were included post-hoc to provide essential theoretical and historical context for the discussion.

3.3. Selection and Data Extraction
The database searches initially identified 467 records. After removing duplicates and screening titles and abstracts, 121 full-text articles were assessed for eligibility. A final corpus of 86 studies met all inclusion criteria and was included in the qualitative synthesis.
For each included study, bibliographic details (author, year, title) and methodological characteristics (research method, thematic focus) were extracted. The studies were then coded into three analytical categories for synthesis: technical, pedagogical, and conceptual. This classification enabled both quantitative trend analysis and qualitative interpretation, forming the basis for the proposed metaverse-based pedagogical framework.

3.4. Analytical Orientation
The conceptual synthesis is structured around three interrelated themes:
- Interactive and collaborative learning,
- Technological infrastructure and design tools,
- Pedagogical innovation through immersive environments.

By consolidating findings across these themes, this study proposes theoretical models and practical recommendations for integrating metaverse technologies into architectural education. While this conceptual approach provides a broad analytical scope, it does not incorporate primary data collection. Consequently, future research is recommended to empirically validate the proposed framework through educator surveys, student feedback, and design-studio case studies.

4. ARCHITECTURAL EDUCATION in RETROSPECt
Architecture has evolved from ancient monuments to technology-driven modern designs, influencing architectural education. Traditionally, it combined theoretical classroom learning with practical workshop training [42]. Ancient education blended intellectual study of geometry and materials with practical experience of construction [43]. The Middle Ages emphasized geometric precision, while the Renaissance, with figures like Alberti, formalized architecture as a technical and theoretical art [44], paving the way for academies, notably the École des Beaux-Arts in 1789 [45]. The 19th century saw global institutionalization, with architectural history becoming central [46]. Formal architecture schools emerged, providing structured curricula encompassing design, structural technology, history, and theory. In the 20th century, movements like Bauhaus and the International Style further reshaped architectural education, emphasizing functionality and modern materials [47].
While sometimes considered outdated, traditional teaching methods effectively ground students in architecture. In-class discussions and site visits provide direct experience [48]. Lecture topics and term projects foster deeper exploration and independent research [49, 50]. However, these methods often fail to meet the expectations of digital-native students seeking interactive learning. Modern education requires technology-driven approaches that foster innovation, collaboration, and practical engagement, shifting towards a student-centered model [51]. Accessible technologies have consistently transformed architectural education by providing efficient design tools for complex forms [52]. This evolution creates a dynamic learning environment, better preparing students for contemporary challenges [53]. Emerging trends include VR and AR integration, enabling virtual exploration of architectural masterpieces, enriching the educational experience [53].

5. VIRTUAL and ELECTRONIC ARCHITECTURAL EDUCATION
The COVID-19 pandemic significantly accelerated online education [26]. Technology and digital tools reduced reliance on physical classrooms [54]. Universities rapidly adopted online platforms, leading to a surge in digital communication and collaboration, prompting increased corporate investment in the digital domain [32]. Distance

learning offers several advantages, including reduced economic barriers, minimized time and location constraints, decreased transportation needs, enhanced knowledge sharing, increased participation, and reduced instructor influence [55]. It also provides rich resources and encourages contemplation and collaboration [23]. Consequently, e-learning, encompassing online courses and virtual collaboration tools, including XR, AR, VR, and MR (Table 1), has become essential [26].

To maximize learning benefits, understanding the advantages and technical considerations of these technologies is crucial [27, 61, 62] (Table 2). The evolution of architectural education through virtual and electronic platforms enhances learning and prepares students for the digital landscape. Embracing these innovations is essential for cultivating architects equipped to navigate modern design and collaboration.

Table 1. Overview of XR, AR, MR, and VR Technologies [56- 60]

Term	**Definition**	**Capabilities and Benefits**	**Tools**	**Challenges/Drawbacks**
XR (Extended Reality)	XR is an umbrella term for Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), combining these technologies to enhance teaching and learning.	It creates interactive environments and boosts creativity, realism, and participation in classrooms.	VR headsets, AR glasses, and MR tools	- Fragmentation of platforms can complicate integration - Potential high costs for equipment - Varying levels of user comfort and experience
AR (Augmented Reality)	It enhances the real world by linking digital content to specific locations or activities.	It enhances user interaction and understanding of their surroundings, immersing users in digital content.	Smartphones, tablets, specialized glasses	- Limited effectiveness in poorly lit environments; may require a strong internet connection - It can be less immersive compared to VR.
VR (Virtual Reality)	It utilizes computer technology to create immersive, 360-degree environments that can be explored, placing users in a virtual space.	It provides immersive, interactive learning, access to inaccessible environments, increased empathy, and remote learning.	VR headsets	- Complex technology - Potential lack of educational strategy - not always leading to better learning outcomes - Can cause motion sickness in some users.
MR (Mixed Reality)	It combines the real and virtual worlds, allowing digital objects to interact with physical environments.	It fills gaps in traditional education due to resource limitations and safety concerns.	MR headsets and tools	- Requires high computing power and advanced technology - Can be expensive - Potential challenges with accurately integrating digital objects into physical spaces.

Table 2. 2D vs. 3D Learning Environments Comparison (authors)

Comparison of 2D vs. 3D Learning Environments		
Aspect	**2D Learning Environments**	**3D Learning Environments**
1. User Engagement	Lower Immersion	High Immersion
	Limited Interaction	Real-time Interaction
2. Collaboration	Text-based communication	Virtual presence
	Video calls	Interactive 3D models
3. Spatial Understanding	Flat representation	True depth perception
	Limited depth perception	Realistic simulations
4. Technical Challenges	Lower hardware requirements	Requires high-end hardware
	Easier access	Complex integration
5. Accessibility	More affordable	Costly equipment
	Less equipment needed	Requires VR headsets

6. A PRELUDE to the METAVERSE and Its POTENTIALS in EDUCATION

The term "Metaverse," combining "meta" (beyond) and "universe," refers to a virtual reality world powered by Augmented Reality (AR) and Artificial Intelligence (AI) [63]. Its conceptual roots trace back to Neal Stephenson's 1992 novel Snow Crash, which introduced the term, and William Gibson's 1984 novel, which featured "The Matrix"—a metaverse precursor [13, 32, 64]. Global awareness significantly increased in 2021 when Facebook rebranded as Meta, led by Mark Zuckerberg [63, 64].

Experts define the metaverse as a 3D virtual reality where users, through avatars, conduct daily activities, effectively merging real and virtual worlds [65]. It encompasses four main categories: AR, lifelogging, mirror worlds, and Virtual Reality (VR) [35]. Operating beyond traditional internet and mobile technologies, it functions as a 3D virtual world integrating VR, AR, Extended Reality (XR), Mixed Reality (MR), and blockchain, providing a multi-dimensional, immersive experience [64, 66]. Users access these environments via devices ranging from laptops and mobile phones to high-fidelity VR headsets [66].

Metaverse designers aim for immersive, emotional experiences, and to enhance interaction, the environment relies heavily on digital avatars and Deep Learning (DL)-based advancements [63]. Machine learning algorithms process user commands, voice recognition, and Natural Language Processing (NLP) records social and business activities, analyzes meetings, and accurately responds to queries. Furthermore, sound is crucial for auditory immersion, requiring effective processing for speech-to-text and spatial audio cues [67].

6.1. Technical Challenges and Computational Frameworks in Metaverse-Based Learning

While the pedagogical implications of the metaverse are often emphasized in educational discourse, its successful implementation in architectural learning environments depends fundamentally on computational robustness. The convergence of AI, real-time rendering, and network optimization determines whether immersive experiences can genuinely simulate the complexity of architectural design studios. Several interrelated technical challenges must therefore be addressed to ensure scalability, responsiveness, and interoperability across metaverse platforms.

A. AI-Driven Interaction and Adaptive Environments

Intelligent avatar systems are essential for supporting rich, interactive pedagogical scenarios—serving as tutors, peers, or assistants. Recent advances in generative AI models (e.g., transformer-based architectures) permit avatars that respond to student input via natural language, conduct context-aware tutoring, or generate adaptive prompts [68].

Nonetheless, integrating such models in real time imposes computational burdens: specifically, inference latency, memory constraints, and the risk of inconsistent or biased responses must be mitigated. One promising strategy involves distilled models or edge-deployed lightweight transformer variants that reduce payloads without sacrificing responsiveness.

B. Latency, Synchronization, and Rendering Performance

Maintaining ultra-reliable and low-latency transmission is a critical requirement for AR/VR applications and immersive metaverse environments, as the stringent quality-of-service (QoS) constraints directly influence real-time interaction, user comfort, and system responsiveness [69].

End-to-end delay in these environments typically arises from three primary sources: network transmission latency, rendering pipeline computation, and synchronization overhead among distributed clients.

To enhance rendering performance in XR and metaverse environments, 5G networks facilitate the transmission of compressed image and pose data between VR devices and edge cloud servers. This architecture supports real-time interaction by shifting computational tasks closer to the user, thereby reducing latency and improving frame stability [70].

This hybrid approach is coupled with 5G or Wi-Fi 6 networks to enable real-time multi-user synchronization and continuous BIM data streaming. Additional latency mitigation is achieved through predictive tracking algorithms and motion extrapolation, allowing rendering engines to anticipate user movement and compensate for network delay, as implemented in platforms like Microsoft Mesh and NVIDIA Omniverse.

C. Data Interoperability and System Integration

One of the most persistent technical barriers to deploying metaverse environments in architectural education is the lack of robust interoperability between conventional design tools and immersive platforms. Architectural workflows rely on complex Building Information Modeling (BIM) and Computer-Aided Design (CAD) data, which encode both geometry and crucial semantic attributes. When models are exported to real-time engines, substantial information loss—including broken hierarchies or missing textures—can occur, undermining spatial accuracy.

The translation of this parametric and semantic data across platforms is computationally expensive. While exchange formats like Industry Foundation Classes (IFC), Universal Scene Description (USD), and glTF attempt to standardize data, inconsistencies persist. For instance, Unreal's Datasmith can import Revit models but often strips parametric relationships. To preserve fidelity, research has proposed middleware abstraction layers and ontology-based translation frameworks that act as intermediaries [71].

Meshreduce uses mesh decimation, texture compression, and distributed processing to enable efficient real-time streaming of large-scale 3D scenes with low latency and bandwidth. By offloading reconstruction tasks to edge devices, it scales effectively across multiple sensors and complex environments, ensuring coordinate and scale consistency an aspect critical for architectural pedagogy [72].

D. Comparative Platform Requirements

The effectiveness of metaverse-based architectural education depends on harmonizing these technical dimensions AI, latency management, and interoperability within feasible hardware and network conditions. As summarized in Table 3, metaverse environments differ substantially in their technical foundations. Platforms like Meta Horizon and Microsoft Mesh prioritize high-fidelity rendering and enterprise-level collaboration through proprietary cloud infrastructures, while Decentraland and Roblox Studio emphasize accessibility and low-latency browser experiences. Understanding the specifications including average end-to-end latency tolerance, concurrency limits, AI integration capacity, and interoperability with BIM/3D tools is indispensable for transforming the metaverse from a conceptual promise into a reliable pedagogical medium.

Table 3. Comparative Technical Requirements and Capabilities of Selected Metaverse Platforms for Architectural Education [73- 79]

Platform	Rendering Engine / Technology	Average Latency Range	AI/Avatar Interaction Capability	Network & Computing Architecture	Hardware Requirements	Typical Use in Architectural Education
Meta Horizon Workrooms	Unity + Oculus SDK	Not specified	VR avatars with hand tracking	Cloud-based edge rendering (Meta Servers)	Oculus Quest 2/3, PC VR	Collaborative design critique, virtual studio meetings
Microsoft Mesh	Unity + Mesh Toolkit	Not specified	Digital avatars for VR interaction	Cloud-based processing via Azure	HoloLens 2, high-end PC, 5G	Cross-platform collaboration, mixed-reality design review
NVIDIA Omniverse	OpenUSD, RTX Path-Tracing, Omniverse Nucleus, Omniverse ACE (AI avatars)	Typically 15–40 ms for local sessions; higher latency may occur in cloud-based deployments.	Medium-High – AI physics, scene optimization	GPU-accelerated local/cloud rendering	Workstation GPU (RTX A-series)	Real-time collaborative design, digital twin visualization, immersive walkthroughs, AI-assisted critique sessions
Unreal Engine / Epic Metahuman	Unreal Engine 5, MetaHuman Creator, MetaHuman Animator, Datasmith, Pixel Streaming	20–60 ms	High – AI-driven lifelike avatars	Client-server/edge deployment	High-end GPU, VR HMD	Immersive design studios, VR walkthroughs
Roblox Studio	Proprietary Lightweight Engine	80–150 ms (server load)	Low-Medium – limited AI, rule-based NPCs	Centralized cloud servers	Mid-range PC / tablet	Introductory VR learning, low-cost collaboration
Decentraland	WebGL / Babylon Engine	100–180 ms (web latency)	Low-scripted NPCs only	Blockchain-based distributed network	Browser / mid-range PC	Public exhibitions, virtual campuses
Spatial.io	Unity WebXR Engine	30–80 ms	Medium – AI moderation, voice recognition	Cloud rendering with edge delivery	Browser / VR headset	Cross-platform presentation, student critiques

Table 3 provides a high-level, relative comparison of technical requirements and capabilities across leading Metaverse platforms, with a focus on applications in architectural education. While the data reflects current industry consensus on relative strengths (e.g., NVIDIA Omniverse excels in data interoperability, and Roblox in scalability), key metrics should be interpreted with caution. Specifically:

- Latency ranges are optimal estimates and highly dependent on user network quality, geographical location, and whether the processing is local (e.g., Omniverse) or cloud-based. Consistent low latency (e.g., sub-30 ms) is challenging to maintain in multi-user settings.
- Data interoperability is generalized; "High" (e.g., Mesh, Unreal) implies support for structured AEC formats via specialized plugins (Datasmith, Azure Digital Twins, IFC), whereas "Moderate" (e.g., Workrooms, Spatial) typically means limited, unoptimized import of basic 3D geometry (FBX, GLB) without BIM metadata.
- AI/Avatar capabilities are evolving rapidly, and current labels may quickly become outdated as platforms like Roblox and Meta invest heavily in generative AI and cognitive agents.

7. The Role of Metaverse in the Training of the Future Generation of Architects

Historically, education has consistently adopted new techniques and tools. Today, the emergence of the metaverse as the digital landscape of the future offers a unique opportunity for significant transformation in education [80]. To meet the new generation's demand for 3D, interactive virtual experiences (e.g., games and animations), educational systems must adapt [81]. The metaverse surpasses 2D platforms, offering immersive 3D learning and facilitating active, student-centered education. This potential for transformation in architectural education is not just exciting but also inspiring, as it opens up new possibilities for learning and teaching in the field.

The metaverse integrates formal and informal education within 3D virtual campuses, allowing students to own virtual spaces and curricula. It offers immense potential for laboratory simulations and procedural skill development, enabling a deeper understanding and safe practice. By providing visual and interactive experiences, it enhances learning engagement and accessibility, potentially accelerating learning and improving performance [82]. The metaverse's 3D virtual space facilitates location- and time-independent learning, providing access to high-quality education for all and fostering student-instructor interaction and collaboration [82]. The virtual reconstruction of Temple University's campus in Second Life exemplifies this, creating interactive learning environments for virtual class participation and campus engagement [41].

The metaverse's 3D virtual space introduces a new paradigm in education, enabling location- and time-independent learning and providing accessible, high-quality education for all, fostering student-instructor interaction and collaboration [82]. The virtual reconstruction of Temple University's campus in Second Life exemplifies this. This project created a precise digital replica of a university campus, providing interactive learning environments for virtual class participation and campus engagement. These metaverse applications enhance learning and support interactive education in virtual spaces [41].

The metaverse is increasingly relevant in architecture and tourism, particularly in cultural heritage preservation. Studies show it serves as a shared space for recreating and preserving cultural heritage. Virtual environments incorporating historical architectural archetypes allow users to connect with cultural memory [83]. Metaverse applications in museums enhance inclusivity and engagement through digital twins and virtual tours, expanding reach and contributing to heritage preservation [84]. The metaverse's vast potential remains a topic of ongoing discussion.

The metaverse overcomes 2D architectural education limitations by providing 3D, interactive experiences. Students can engage with professors and experts in virtual campuses. For instance, a historical architecture course utilized a detailed 3D digital model of the Tomb of Pashedu III as an interactive documentary for teaching architectural history, archaeology, and art [16]. This demonstrates the metaverse's potential to enrich architectural education. A study of seven Virtual Architectural Design Studios (VADS) at an Australian university showed VADS create positive learning environments through increased flexibility, ideation support, and global collaboration [85]. These findings suggest that VADS provide a foundation for future metaverse-based architectural education. By overcoming these traditional limitations, the metaverse empowers educators and students to think and learn in new, innovative ways.

The metaverse significantly enhances architectural education through improved immersion, interaction, and technical skills. Students experience designs at full scale, understanding depth and proportions, interacting with elements, observing real-time modifications, and exploring building performance simulations. This deepens design functionality understanding. Beyond technical skills, the metaverse fosters creativity, innovation, and interpersonal abilities. It provides a flexible environment for experimentation and creative problem-solving, with customizable lesson plans nurturing individual interests. Collaboration is enhanced through virtual project work, design presentations to diverse audiences, and connections with global professionals. However, the metaverse presents technical, educational, and social challenges. Technically, platform diversity complicates optimal selection. Metaverse platforms, which are digital environments facilitating virtual interaction and 3D space creation, such as Unity or Unreal Engine, offer immersive experiences beyond traditional e-learning. However, compatibility issues with specialized architectural software, such as Revit and SketchUp, create significant hurdles. Additionally, advanced equipment like VR

headsets and powerful computers may be unaffordable for all students.

Educationally, creating effective metaverse content for intricate architectural concepts is complex. Students require technical skills and computer literacy, which may not be universal. Like other e-learning, metaverse use can increase student isolation due to physical and temporal separation, hindering collaboration [86]. Social and ethical challenges also exist. While developers attempt to replicate face-to-face interaction, real-life interaction cannot be entirely replaced. Over-reliance on the metaverse can lead to isolation and distractions, significantly hindering learning. Ethically, student personal data collection must adhere to privacy laws, and intellectual property rights for metaverse-created content must be clearly defined to ensure trust and protect student and educator rights.

8. Proposed Solutions

Addressing the challenges of metaverse integration in architectural education requires targeted solutions. First, developing specialized metaverse platforms compatible with architectural software is crucial to ensuring seamless interaction, real-time collaboration, and effective feedback between students and instructors. Second, creating engaging, interactive educational content is essential for conveying complex architectural concepts and enhancing student participation. Additionally, comprehensive training for both students and instructors is vital to maximizing the technology's potential. Clear guidelines must also be established to protect privacy, safeguard intellectual property, and ensure student well-being. Finally, further research is needed to assess the efficacy of metaverse applications and refine strategies for overcoming existing barriers. A structured approach that encompasses technological infrastructure, pedagogical advancements, training, and regulatory frameworks will enable educators and students to leverage immersive virtual environments fully.

A. Developing Specialized Metaverse Platforms

Developing metaverse platforms that are compatible with architectural software such as AutoCAD, Revit, Rhino, SketchUp, and BIM is crucial. BIM, a transformative tool integrating design, construction, and management, enables real-time collaboration and data sharing. Incorporating BIM into metaverse platforms allows students and instructors to import, visualize, and manipulate complex 3D models, facilitating the assessment of building performance. These platforms should seamlessly integrate architectural software with immersive environments, enabling interactive spatial exploration and design refinement. They should also emulate physical design studios by fostering collaboration, peer feedback, and real-time interaction, ensuring a comprehensive educational experience.

B. Creating Interactive and Engaging Educational Content

Developing high-quality, interactive content tailored to architectural pedagogy is vital. This content should offer immersive simulations and virtual walkthroughs of iconic architecture, real-world projects, and construction processes, effectively conveying complex concepts like spatial relationships and material behavior. Interactive design challenges and collaborative projects can boost student motivation and participation in metaverse learning. Gamification techniques, such as points for task completion and real-time design feedback, can further enhance engagement.

C. Comprehensive Training for Students and Instructors

Comprehensive training programs for students and instructors are crucial for successful metaverse adoption. These programs should cover metaverse platform technicalities, including navigation, 3D model uploads, and virtual collaboration. Instructor training should focus on adapting traditional teaching to immersive metaverse experiences and providing real-time progress feedback. Digital literacy workshops can help students and faculty overcome the learning curve, ensuring confident metaverse tool use and enhancing the educational experience.

D. Establishing Guidelines and Regulatory Frameworks

Clear guidelines and regulations are necessary for privacy protection, intellectual property rights, and ethical considerations. Student personal data must be securely managed within metaverse platforms, and creative works must be protected from unauthorized use. Guidelines should ensure safe and inclusive virtual environments, with clear policies on virtual conduct, screen time, and mental health to mitigate risks like virtual fatigue and isolation. Monitoring mechanisms should be developed to track student engagement in virtual environments, balancing privacy with oversight. These tools should ensure focus and active participation, while also preventing overuse. Supervision can include regular check-ins, automated attendance tracking, and analytical tools to identify disengagement or overuse, enabling timely interventions.

E. Conducting Further Research and Continuous Improvement

Further research is imperative to assess the metaverse's efficacy in architectural education. Studies should evaluate learning outcomes in comparison to traditional environments, gathering both quantitative and qualitative data on student performance, engagement, and satisfaction. Pilot programs should test platform scalability across architectural institutions. Research must identify and address technical challenges, such as accessibility and bandwidth. Continuous improvement based on student and instructor feedback is essential for long-term platform success.

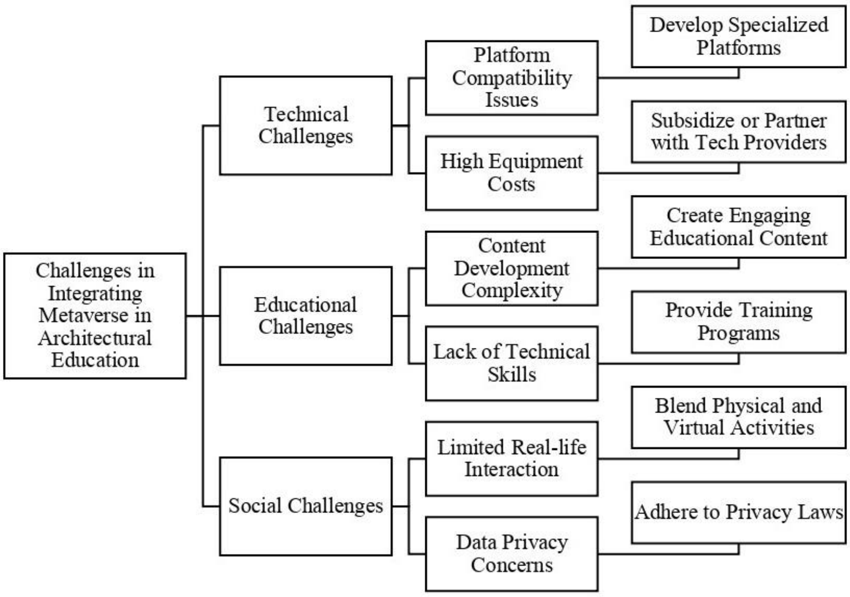


Figure 1. Metaverse Integration Challenges & Solutions

Table 4. SWOT Analysis of the Role of Metaverse in the Education of Architecture

	Immersive Learning	**Deep engagement through virtual environments**
Strengths	Interactive Experience	Active participation with real-time interactions
	Empowering Creativity	Enhances innovation through experimentation
	Spatial Understanding	Improved grasp of spatial relationships and proportions
	Collaboration	Facilitates teamwork and group communication
	Global reach	Provides worldwide access to educational opportunities
	International collaboration	Enables cooperation with professionals globally
	Simulation-based learning	Teaches using realistic process and project simulations
	Practical application	Applies knowledge to real-world scenarios effectively
Weaknesses	Advanced equipment	High cost of devices like VR headsets and powerful hardware
	Accessibility issues	Limited access due to financial or technical barriers
	Digital skills	Needs training in metaverse tools and platforms
	Costly content development	High costs of developing immersive, interactive materials
	Complexity in content creation	Challenges in simplifying complex concepts for virtual learning
	Engaging content challenges	Creating content that captivates and sustains learner interest
Opportunities	Wider adoption	Potential for broader adoption in universities
	Innovation	Creation of innovative teaching methods and tools
	Interpersonal skills	Boosts collaboration and communication in virtual teams
	High-quality education	Provides superior resources and immersive learning
	Remote access	Allows education beyond physical boundaries
	Students engagement	Enhances engagement via interactive, immersive environments
	Collaborative learning	Fosters teamwork and knowledge-sharing in virtual spaces
Threats	Privacy concerns	Risk of misuse or unauthorized access to users' personal data
	Data security	Vulnerability to cyberattacks and breaches on virtual platforms
	Safeguarding intellectual property	Challenges in protecting digital creations and designs
	Legal challenges	Ambiguous regulations for metaverse use in education
	Ethical issues	Excessive use of virtual environments weakens real-world ties.
	Limited real-life interaction	Reduced face-to-face interaction may impact collaboration and social skills.

9. Conclusion

The advent of metaverse-based architectural training signifies a paradigm shift in online education. While traditional pedagogical models centered on physical classrooms, recent global exigencies have necessitated learning environments that transcend spatial constraints. Traditional e-learning platforms, although they offer virtual communication, often fail to provide the immersive and interactive experiences crucial for disciplines such as architecture. The emergence of three-dimensional e-learning via the metaverse revolutionizes educational methodologies, offering novel avenues for enhanced comprehension and engagement. Integrating virtual reality environments into architectural pedagogy represents a transformative approach, mitigating the limitations of conventional methods. Despite challenges about infrastructure, digital literacy, and content development, the metaverse's educational potential remains substantial. Through strategic planning and implementation (Figure 1), these challenges can be effectively addressed, thereby augmenting educational quality globally. Architectural education, inherently reliant on visual and spatial acuity, demands experiences beyond two-dimensional modalities. The metaverse, with its 3D interactive spaces, offers a potent tool for enhancing student learning and skill acquisition.

This study has critically assessed the limitations of traditional pedagogical frameworks, evaluated the efficacy of online learning, and explored the transformative potential of metaverse-based three-dimensional education within architectural disciplines. We propose a future educational paradigm where the metaverse enables immersive learning experiences, equipping students with the skills needed to navigate the complexities of a digitalized built environment. Employing the metaverse as a pedagogical tool redefines architectural education, fostering creativity, collaborative learning, and enhanced spatial cognition. The integration of metaverse technologies into architectural pedagogy represents a transformative trajectory, cultivating an ecosystem of continuous learning, interactive engagement, and enriched experiential outcomes (Table 4). The future trajectory of architectural education lies within the metaverse—a nascent frontier with substantial potential for immersive and collaborative pedagogical advancements. Embracing this paradigm will propel architectural education into novel dimensions, equipping future architects with the adaptability and proficiencies necessary to navigate an increasingly complex global context.

References:

[1] R. G. Hershberger. (1970). Architecture and meaning. *Journal of Aesthetic Education*. [Online]. *4(4)*, pp. 37–55. Available: https://doi.org/10.2307/3331285

[2] L. S. Martyshova, "Modern features and trends in the development of the architectural education system," in Proceeding 9th Annual International Conference on Current Issues of Education and Science (CIES 2021), Riga, Latvia – Kharkiv, Ukraine, 2021. Available: https://doi.org/10.26697/9786177089147.2021

[3] A. B. Daemei & H. Safari. (2018). Factors affecting creativity in the architectural education process based on computer‐aided design. *Frontiers of Architectural Research*. [Online]. *7(1)*, pp. 100–106. Available: https://doi.org/10.1016/j.foar.2017.09.001

[4] A. Bergström. (2014). Architecture and the rise of practice in education. *Architectural Theory Review*. [Online]. *19(1)*, pp. 10–21. Available: https://doi.org/10.1080/13264826.2014.894604

[5] S. Kurt. (2018). Assessing the quality of architecture schools. *Quality & Quantity*. [Online]. *52(S1)*, pp. 863–888. Available: https://doi.org/10.1007/s11135-018-0695-8

[6] S. S. Shareef & G. Farivarsadri. (2020). An innovative framework for teaching/learning technical courses in architectural education. *Sustainability*. [Online]. *12(22)*, p. 9514. Available: https://doi.org/10.3390/su12229514

[7] F. D. Susi. (1986). Physical space and the teaching of art. *Art Education*. [Online]. *39(2)*, pp. 6–9. Available: https://doi.org/10.1080/00043125.1986.11649731

[8] V. Ng, T. S. Mari, & C. L. Lin. (2022). Re‐thinking architecture education: Conceptualising curriculum through the lens of 21st‐century graduate attributes. *Journal of Design and Built Environment*. [Online]. *22(2)*, pp. 85–92. Available: https://doi.org/10.22452/jdbe.vol22no2.6

[9] F. Mantovani, "VR learning: Potential and challenges for the use of 3D environments in education and training," In *C. Galimberti (Ed.), Towards Cyberpsychology: Mind, Cognition, and Society in the Internet Age*, vol. 2, 2001, pp. 207–225. [Online].

[10] H. Agarwal & G. Pandey. (2013). Impact of e‐learning in education. *International Journal of Science and Research (IJSR)*. [Online]. *2(12)*, pp. 146–147. Available: https://www.academia.edu/download/38591031/Impact_of_E-learning_in_education.pdf

[11] S. Goyal. (2012). E‐learning: Future of education. *Journal of Education and Learning (EduLearn)*. [Online]. *6(4)*, pp. 239–242. Available: https://doi.org/10.11591/edulearn.v6i4.168

[12] B. Sidawi. (2013). The tutors' views on the utilization of e‐learning systems in architectural education. *European Journal of Open, Distance and E‐Learning*. [Online]. *16(2)*, pp. 1–12. Available: https://eric.ed.gov/?id=EJ1017527

[13] S. Mystakidis. (2022). Metaverse. Encyclopedia. [Online]. 2(1), pp. 486–497. Available: https://doi.org/10.3390/encyclopedia2010031

[14] T. Can & İ. Sımsek. (2015). The use of 3D virtual learning environments in training foreign language pre‐service teachers. *Turkish Online Journal of Distance Education*. [Online]. *16(4)*, pp. 114–124. Available: https://doi.org/10.17718/tojde.53012

[15] A. Correia, B. Fonseca, H. Paredes, P. Martins, and L. Morgado, "Computer-simulated 3D virtual environments in collaborative learning and training:

Meta-review, refinement, and roadmap," in *Handbook on 3D3C Platforms: Applications and Tools for Three Dimensional Systems for Community, Creation and Commerce*, 2016, pp. 403–440. Available: https://doi.org/10.1007/978-3-319-22041-3_15

[16] A. A. Gaafar. (2021). Metaverse in architectural heritage documentation and education. *Advances in Ecological and Environmental Research*. [Online]. *6(10)*, pp. 66–86.

[17] K. R. Rahman, S. K. Shitol, M. S. Islam, K. T. Iftekhar, & P. Saha. (2023). Use of metaverse technology in education domain. *Journal of Metaverse*. [Online]. *3(1)*, pp. 79–86. Available: https://doi.org/10.57019/jmv.1223704

[18] J. Dewey, "Democracy and Education," in *Columbia University Press*, 2024. [Online]. Available: https://cup.columbia.edu/book/democracy-and-education/9780231210119/

[19] A. A. Nagy, "The impact of e‑learning," In *E‑Content: Technologies and Perspectives for the European Market*, 2005, pp. 79–96. [Online]. Springer. Available: https://doi.org/10.1007/3-540-26387-X_4

[20] A. A. B. Al‑Tammemi et al. (2022). A qualitative exploration of university students' perspectives on distance education in Jordan: An application of Moore's theory of transactional distance. *Frontiers in Education*. [Online]. *7*, p. 960660. Available: https://doi.org/10.3389/feduc.2022.960660

[21] C. N. Gunawardena and M. S. McIsaac, "Distance education," in Handbook of Research on Educational Communications and Technology, pp. 361–401, Routledge, 2013. Available: https://doi.org/10.4324/9780203803730

[22] K. Stecuła & R. Wolniak. (2022). Influence of COVID‑19 pandemic on dissemination of innovative e‑learning tools in higher education in Poland. *Journal of Open Innovation: Technology, Market, and Complexity*. [Online]. *8(2)*, p. 89. Available: https://doi.org/10.3390/joitmc8020089

[23] G. Guohong, L. Ning, X. Wenxian, & W. Wenlong. (2012). The study on the development of internet‑based distance education and problems. *Energy Procedia*. [Online]. *17*, pp. 1362–1368. Available: https://doi.org/10.1016/j.egypro.2012.02.253

[24] A.-M. Tirziu & C. Vrabie. (2015). Education 2.0: E‑learning methods. *Procedia – Social and Behavioral Sciences*. [Online]. *186*, pp. 376–380. Available: https://doi.org/10.1016/j.sbspro.2015.04.213

[25] M. Aparicio, F. Bacao, & T. Oliveira. (2016). An e‑learning theoretical framework. *Educational Technology & Society*. [Online]. *19(1)*, pp. 292–307. Available: https://novaresearch.unl.pt/files/3515333/MAparicio_FBacao_TOliveira_2016.pdf

[26] A. F. Ibrahim, A. S. Attia, B. Asma'M, & H. H. Ali. (2021). Evaluation of the online teaching of architectural design and basic design courses: Case study, College of Architecture at JUST, Jordan. *Ain Shams Engineering Journal*. [Online]. *12(2)*, pp. 2345–2353. Available: https://doi.org/10.1016/j.asej.2020.10.006

[27] S. Mystakidis, E. Berki, & J.-P. Valtanen. (2021a). Deep and meaningful e‑learning with social virtual reality environments in higher education: A systematic literature review. *Applied Sciences*. [Online]. *11(5)*, p. 2412. Available: https://doi.org/10.3390/app11052412

[28] T. Monahan, G. McArdle, & M. Bertolotto. (2008). Virtual reality for collaborative e‑learning. *Computers & Education*. [Online]. *50(4)*, pp. 1339–1353. Available: https://doi.org/10.1016/j.compedu.2006.12.008

[29] D. Guney. (2015). The importance of computer‑aided courses in architectural education. *Procedia – Social and Behavioral Sciences*. [Online]. *176*, pp. 757–765. Available: https://doi.org/10.1016/j.sbspro.2015.01.537

[30] M. M. Saleh, M. Abdelkader, & S. S. Hosny. (2023). Architectural education challenges and opportunities in a post‑pandemic digital age. *Ain Shams Engineering Journal*. [Online]. *14(8)*, p. 102027. Available: https://doi.org/10.1016/j.asej.2022.102027

[31] A. Michael & M. Phocas. (2012). Construction design and sustainability in architecture: Integrating environmental education in the architectural studies. *Renewable Energy and Power Quality Journal*. [Online]. *10(2)*. Available: https://doi.org/10.24084/repqj10.268

[32] P. Schumacher. (2022). The metaverse as an opportunity for architecture and society: Design drivers, core competencies. *Architectural Intelligence*. [Online]. *1(1)*, p. 11. Available: https://doi.org/10.1007/s44223-022-00010-z

[33] H. Sirror, A. Abdelsattar, S. Dwidar, and A. Derbali, "A review on virtual reality for architecture education," in *Proceeding 11th Annual Interantional Conference on Industrial Engineering and Operations Management*, Singapore, 2021.

[34] M. Aljanabi & S. Y. Mohammed. (2023). Metaverse: Open possibilities. *Iraqi Journal for Computer Science and Mathematics*. [Online]. *4(3)*, pp. 79–86. Available: https://doi.org/10.52866/ijcsm.2023.02.03.007

[35] B. Kye et al. (2021). Educational applications of the metaverse: Possibilities and limitations. *Journal of Educational Evaluation for Health Professions*. [Online]. *18*, p. 32. Available: https://doi.org/10.3352/jeehp.2021.18.32

[36] M. Frydenberg and S. Ohri, "Designing a metaverse for an immersive learning experience," in *Proceeding 9th International Conference on Higher Education Advances (HEAd'23)*, pp. 1139–1146, 2023. Available: https://doi.org/10.4995/HEAd23.2023.16080

[37] M. Frydenberg, D. J. Yates, and A. Noonan, "Living in the metaverse: A multidisciplinary course design and pedagogy," *Proceedings of the ISCAP Conference*, vol. 2473, 2023, p. 4901. Available: https://doi.org/10.2139/ssrn.4357523

[38] B. Onecha, C. Cornadó, J. Morros, & O. Pons. (2023). New approach to design and assess metaverse environments for improving learning processes in higher education: The case of architectural construction and rehabilitation. *Buildings*. [Online]. *13(5)*, p. 1340. Available: https://doi.org/10.3390/buildings13051340

[39] M. Cininta, D. Santy, and E. T. Irmayasari, "Innovative approaches to architectural education: Metaverse technology and learning resilience," *IOP Conference Series: Earth and Environmental Science*, vol. 1404, no. 1, 2024, p. 012054. Available: https://doi.org/10.1088/1755-1315/1404/1/012054

[40] M. Tsiliakos and S. Bassing, "Eduverse: Exploring gamification and the metaverse in architectural pedagogy," in *Accelerated Design, Proceeding 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2024)*, vol. 3, 2024, pp. 59–68. Available: https://discovery.ucl.ac.uk/id/eprint/10193155/

[41] H. Sopher & L. Lescop. (2023). Learning in metaverse: The immersive atelier model of the architecture studio. *Archnet‑IJAR: International Journal of Architectural Research*. [Online]. *17(3)*, pp. 536–553. Available: https://doi.org/10.1108/ARCH-10-2022-0213

[42] A. M. Salama, W. O'Reilly, and K. Noschis, "Architectural Education Today: Cross-Cultural Perspectives*," Arti-arch*, 2002.

[43] A. Salama, "New Trends in Architectural Education: Designing the Design Studio," *Arti-arch*, 1995.

[44] M. Johnson, "Behind the Castle Gate: From the Middle Ages to the Renaissance," *Routledge*, 2013.

[45] A. Picon, "Précis of the Lectures on Architecture: With Graphic Portion of the Lectures on Architecture," *Getty Publications*, 2000.

[46] M. Özgüleş, M. Kalman, M. Özyurt, & S. Şahin. (2021). Exploring student perceptions and experiences of different teaching and learning approaches in architectural history education: A comparative case study. *Learning Environments Research*. [Online]. *24*, pp. 269–297. Available: https://doi.org/10.1007/s10984-020-09328-9

[47] B. Kolarevic, "Architecture in the Digital Age," Taylor & Francis, 2003.

[48] D. Neumann. (2002). Teaching the history of architecture in Germany, Austria, and Switzerland: 'Architekturgeschichte' vs. 'Bauforschung'. *Journal of the Society of Architectural Historians*. [Online]. *61(3)*, pp. 370–380. Available: https://doi.org/10.2307/991790

[49] D. Kokotsaki, V. Menzies, & A. Wiggins. (2016). Project‑based learning: A review of the literature. *Improving Schools*. [Online]. *19(3)*, pp. 267–277. Available: https://doi.org/10.1177/1365480216659733

[50] D. Thor, N. Xiao, M. Zheng, R. Ma, & X. X. Yu. (2017). An interactive online approach to small‑group student presentations and discussions. *Advances in Physiology Education*. [Online]. *41(4)*, pp. 498–504. Available: https://doi.org/10.1152/advan.00019.2017

[51] A. N. Z. Sanusi, F. Abdullah, M. H. Kassim, & A. A. Tidjani. (2018). Architectural history education: Students' perception on mobile augmented reality learning experience. *Advanced Science Letters*. [Online]. *24(11)*, pp. 8171–8175. Available: https://doi.org/10.1166/asl.2018.12517

[52] D. Vogel & J. Klassen. (2001). Technology‑supported learning: Status, issues and trends. *Journal of Computer Assisted Learning*. [Online]. *17(1)*, pp. 104–114. Available: https://doi.org/10.1111/j.1365-2729.2001.00163.x

[53] A. Kirkwood & L. Price. (2014). Technology‑enhanced learning and teaching in higher education: What is 'enhanced' and how do we know?. *Learning, Media and Technology*. [Online]. *39(1)*, pp. 6–36. Available: https://doi.org/10.1080/17439884.2013.770404

[54] M. Ouadoud, N. Rida, & T. Chafiq. (2021). Overview of e-learning platforms for teaching and learning. *International Journal of Recent Contributions to Engineering Science & IT*. [Online]. *9(1)*, pp. 50–70. Available: https://doi.org/10.3991/ijes.v9i1.21111

[55] M. Sadeghi. (2019). A shift from classroom to distance learning: Advantages and limitations. *International Journal of Research in English Education*. [Online]. *4(1)*, pp. 80–88. Available: https://doi.org/10.29252/ijree.4.1.80

[56] Y. Huang & Y. Jin. (2022). Research on the impact of the metaverse on the future of social networking. *Journal of Education, Humanities and Social Sciences*. [Online]. *5*, pp. 198–204. Available: https://doi.org/10.54097/ehss.v5i.2902

[57] K. Kamenov, "Immersive Experience—The 4th Wave in Tech: Learning the Ropes," *Accenture*, 2017. Available: https://doi.org/10.2139/ssrn.4067564

[58] P. Milgram, H. Takemura, A. Utsumi, & F. Kishino. (1995). Augmented reality: A class of displays on the reality–virtuality continuum. *Telemanipulator and Telepresence Technologies*. [Online]. *2351*, pp. 282–292. Available: https://doi.org/10.1117/12.197321

[59] K. Schwienhorst. (2002). The state of VR: A meta-analysis of virtual reality tools in second language acquisition. *Computer Assisted Language Learning*. [Online]. *15(3)*, pp. 221–239. Available: https://doi.org/10.1076/call.15.3.221.8186

[60] M. Speicher, B. D. Hall, and M. Nebeling, "What is mixed reality?" in *Proceeding 2019 CHI Conference on Human Factors in Computing Systems*, 2019. Available: https://doi.org/10.1145/3290605.3300767

[61] R. Al-Azawi, A. Albadi, R. Moghaddas, and J. Westlake, "Exploring the potential of using

augmented reality and virtual reality for STEM education," in *Learning Technology for Education Challenges: 8th International Workshop (LTEC 2019)*, Zamora, Spain, Jul. 15–18, 2019, Springer, 2019. Available: https://doi.org/10.1007/978-3-030-20798-4_4

[62] A. Dengel, M. Z. Iqbal, S. Grafe, & E. Mangina. (2022). A review on augmented reality authoring toolkits for education. *Frontiers in Virtual Reality*. [Online]. *3*, p. 798032. Available: https://doi.org/10.3389/frvir.2022.798032

[63] T. Huynh-The et al. (2022). Artificial intelligence for the metaverse: A survey. *Engineering Applications of Artificial Intelligence*. [Online]. *117*, p. 105581. Available: https://doi.org/10.1016/j.engappai.2022.105581

[64] J. Anderson and L. Rainie. (2022). The Metaverse in 2040. Pew Research Center. [Online]. Available: https://www.pewresearch.org/internet/2022/06/30/the-metaverse-in-2040/

[65] S. Go, H. Jeong, J. Kim, & Y. Sin. (2021). Concept and developmental direction of metaverse. *Korea Information Processing Society Review*. [Online]. *28*, pp. 7–16. Available: https://doi.org/10.5626/KIPS2021.28.7

[66] L. U. Khan et al. (2022). Metaverse for wireless systems: Vision, enablers, architecture, and future directions. *IEEE Wireless Communications*. [Online]. *31(4)*, pp. 245–251. Available: https://doi.org/10.1109/MWC.013.2300287

[67] S. Cheng et al. (2022). Roadmap toward the metaverse: An AI perspective. *The Innovation*. [Online]. *3(5)*, p. 100293. Available: https://doi.org/10.1016/j.xinn.2022.100293

[68] H. Zhou, X. Chen, J. Li, Z. Zhang, Y. Fu, M. P. Liva, D. Greenbaum, & P. Hui. (2025). Generative artificial intelligence in the metaverse era: A review on models and applications. *Research*. [Online]. *8*, p. 0804. Available: https://doi.org/10.34133/research.0804

[69] D. Van Huynh, S. R. Khosravirad, A. Masaracchia, O. A. Dobre, & T. Q. Duong. (2022). Edge Intelligence-based Ultra-Reliable and Low-Latency Communications for Digital Twin-enabled Metaverse. *IEEE Wireless Communications Letters*. [Online]. *11(8)*. Available: https://doi.org/10.1109/LWC.2022.3179207

[70] Y. Wang & J. Zhao, "A survey of mobile edge computing for the metaverse: Architectures, applications, and challenges," in *2022 IEEE 8th International Conference on Collaboration and Internet Computing (CIC)*, 2022, pp. 1–9. Available: https://doi.org/10.1109/CIC56439.2022.00011

[71] H. Abdirad, C. S. Dossick, B. R. Johnson, & G. Migliaccio. (2021). Disruptive information exchange requirements in construction projects: Perception and response patterns. *Building Research & Information*. [Online]. *49(2)*, pp. 161–178.

[72] Jin, Tao, et al. "Meshreduce: Scalable and bandwidth efficient 3d scene capture," *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2024. Available: https://doi.org/10.1109/VR58804.2024.00026

[73] Meta, "Introducing Horizon Workrooms: Remote Collaboration Reimagined," Meta Newsroom. [Online]. Aug. 19, 2021. Available: https://about.fb.com/news/2021/08/introducing-horizon-workrooms-remote-collaboration-reimagined. [Accessed: Oct. 8, 2025].

[74] Microsoft, "Microsoft Mesh overview," Microsoft Learn. [Online]. July 28, 2025. Available: https://learn.microsoft.com/en-us/mesh/overview. [Accessed: Oct. 11, 2025].

[75] NVIDIA Corporation, "Accelerate Industrial AI with Omniverse on DGX Cloud," NVIDIA. [Online]. Available: https://www.nvidia.com/en-us/data-center/omniverse-dgx-cloud/. [Accessed: Sept. 13, 2025].

[76] Epic Games, Inc., "Architecture, Unreal Engine". [Online]. Available: https://www.unrealengine.com/en-US/uses/architecture. [Accessed: Sept. 23, 2025].

[77] Roblox Corporation, "Computer Hardware & Operating System Requirements," Roblox Support. [Online]. Available: https://en.help.roblox.com/hc/en-us/articles/203312800-Computer-Hardware-Operating-System-Requirements. [Accessed: Oct. 9, 2025].

[78] Decentraland DAO, "[DAO: bafkrei] Develop new Low Latency Video Streaming components for SDK and builder," Decentraland Forum. [Online]. July 25, 2022. Available: https://forum.decentraland.org/t/dao-bafkrei-develop-new-low-latency-video-streaming-components-for-sdk-and-builder. [Accessed: Oct. 5, 2025].

[79] Spatial Systems, Inc., "Metaverse Avatars: Create & Reinvent Yourself," Spatial. [Online]. 2023. Available: https://www.spatial.io/create-an-avatar. [Accessed: Oct. 19, 2025].

[80] J. Singh, M. Malhotra, & N. Sharma. (2022). Metaverse in education: An overview. *Applying Metalytics to Measure Customer Experience in the Metaverse*. [Online]. pp. 135–142. Available: https://doi.org/10.4018/978-1-6684-6133-4.ch012

[81] H. Lin, S. Wan, W. Gan, J. Chen, and H.-C. Chao, "Metaverse in education: Vision, opportunities, and challenges," in *Proceeding 2022 IEEE International Conference on Big Data (Big Data)*, pp. 2857–2866, 2022. Available: https://doi.org/10.1109/BigData55660.2022.10021004

[82] F. De Felice, A. Petrillo, G. Iovine, C. Salzano, & I. Baffo. (2023). How does the metaverse shape education? A systematic literature review. *Applied Sciences*. [Online]. *13(9)*, p. 5682. Available: https://doi.org/10.3390/app13095682

[83] A. Moneta. (2020). Architecture, heritage, and the metaverse. *Traditional Dwellings and Settlements Review*. [Online]. *32(1)*, pp. 37–49. Available: https://doi.org/10.2307/26915449

[84] J. Hutson & P. Hutson. (2023). Museums and the Metaverse: Emerging Technologies to Promote Inclusivity and Engagement. *IntechOpen*. [Online]. Available: https://doi.org/10.5772/intechopen.110044
[85] R. Yu and N. Gu, "Future learning in the metaverse—An exploration of virtual architectural design studios," in Cultural Space on Metaverse, pp. 3–26, Springer, 2023. Available: https://doi.org/10.1007/978-981-99-2314-4_1
[86] N. Croft, A. Dalton, & M. Grant. (2010). Overcoming isolation in distance learning: Building a learning community through time and space. *Journal for Education in the Built Environment*. [Online]. *5(1)*, pp. 27–64. Available: https://doi.org/10.11120/jebe.2010.05010027